SPACE FLYABLE Hg^+ FREQUENCY STANDARDS*

John D. Prestage and Lute Maleki
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Abstract

We discuss a design for a space based atomic frequency standard (AFS) based on Hg^+ ions confined in a linear ion trap. This newly developed AFS should be well suited for space borne applications because it can supply the ultra-high stability of a H-maser but its total mass is comparable to that of a NAVSTAR/GPS Cesium clock, i.e., about 11 kg. This paper will compare the proposed Hg^+ AFS to the present day GPS Cesium standards to arrive at the 11 kg mass estimate. The proposed space borne Hg^+ standard is based upon the recently developed extended linear ion trap architecture which has reduced the size of existing trapped Hg^+ standards to a physics package which is comparable in size to a Cesium beam tube. The demonstrated frequency stability to below 10^{-15} of existing Hg^+ standards should be maintained or even improved upon in this new architecture. This clock would deliver far more frequency stability per kilogram than any current day space qualified standard.

Introduction

Isolation from environmental perturbations drives the technology and development of all atomic frequency standards. The choice of atom used as the frequency discriminating element in a passive atomic frequency standard determines the sensitivity to external perturbations and consequently the degree to which shielding from these environmental changes will be necessary to reach a given level of stability. Because shielding, usually magnetic and thermal, adds a great deal to the bulkiness and complexity, it is especially important for space borne clocks, where low mass and high reliability are paramount, that the standard be inherently immune to environmental changes so that only modest shielding is required. Mercury ions with their relatively large hyperfine clock resonance frequency and large atomic mass are far more immune to environmental changes than any of the other microwave standards, i.e., hydrogen masers, rubidium gas cells, and cesium beam standards. For example, the fractional frequency shift with magnetic field, $(1/\nu_0)d\nu/dH \propto H/\nu_0^2$ where H is the magnitude of the C-field and ν_0 is the hyperfine clock transition frequency. For the same C-field bias the 40.5 Hg^+ transition is less sensitive to ambient field changes than Cesium (by 19×), Rubidium (by 35×) and Hydrogen (by 837×). This is very important for space borne standards where the spacecraft magnetic environment is much more variable than an earth based frequency standards laboratory. The extra shielding required for the harsher environment thus contributes even more to the clock mass which comes at a premium.

Similarly, H-masers require 10^{-4} °C active temperature regulation to reach 10^{-15} frequency stability while GPS Cesium clocks require 0.1 °C temperature stability to reach 10^{-14}. By contrast, the Hg^+ frequency standard requires 0.1 °C temperature stability to reach 10^{-15} frequency stability, showing that Hg^+ is additionally the most immune to environmental temperature changes. These comparisons demonstrate that this standard is an attractive candidate for space borne applications.

Applications of Space-based Ultra-stable Clocks

There are several uses, scientific and operational for stable atomic frequency standards on board spacecraft in earth orbit, planetary orbit or flyby, and interplanetary cruise mode. In generating Doppler data the ground based antenna observation time is reduced greatly for s/c navigation at the outer planets when the two way uplink-s/c transpond-downlink round trip is replaced by the one-way downlink from the s/c to earth station. This reduces the burden on ground based tracking facilities as the number of spacecraft to be tracked grows larger. There are other advantages for the one way downlink. In the absence of an uplink, media propagation errors and noise sources are reduced by one half. Additionally, when the ground station is configured for listen only operation, the receiver noise temperature is lower[1].

The scientific uses for ultra-stable atomic standards on board spacecraft include tests of gravitational theories and detection of low frequency gravitational waves. For example, an ulta-stable clock aboard a Solar Probe approaching the sun's center to within 4 solar radii could measure the gravitational redshift with an accuracy of a few parts in 10^9, nearly 5 orders of magnitude improvement over present day tests[2].

Another class of scientific applications that will be improved upon with an on-board clock of better stability is the remote sensing of planetary atmospheres during occultation of the s/c. The pressure vs. temperature of the planet's atmosphere can be derived from the phase variation of the radio signal during occultation [1,3].

Navigation on and near the earth's surface is being revolutionized through the spaced based atomic clocks which comprise the Global Positioning System. Rubidium and Cesium standards aboard these satellites generate time coded signals to broadcast to Earth based receivers. Small handheld receivers process signals simultaneously recieved from different spacecraft to determine the users position with an accuracy of meters.

Survey of Space-based Atomic Frequency Standards

GPS/GLONASS Cesium Clocks

Although still in its youth, the technology of space based clocks is being refined through the development of the NAVSTAR/GPS and GLONASS programs. The GPS program has launched 40 satellites into orbits of 12 hours at altitude 20,000 km each with three to four AFSs and backup VCXOs [4,5].

Similary, the Russian GLONASS program has launched several navigation satellites with multiple redundant clocks on board.

In this section we review the physical characteristics of the cesium clocks aboard the NAVSTAR and GLONASS spacecraft since these are probably the most advanced space based clocks yet developed. Although the GPS satellites have flown more Rb standards, the Cs standards are considered primary because of their much lower frequency drift and environmental sensitivities [5]. Additionally, as will be shown, the Hg^+ LITE standard can be made similar in physical size and layout to the Cs beam standard.

Table I summarizes some of the features of the GPS and GLONASS clocks. The masses of the GPS Cs AFSs ranges from 13 kg for Block II standards to 8 kg for the Block IIR replacement clocks[6]. These values are for the clock alone and do not include approximately 1.8 kg (4 pounds) of radiation shielding to protect the standard from natural and potential manmade radiation sources.

The GLONASS clocks are somewhat more massive and bulky [7]. The MALAKHIT is an improvement over the GEM spaceborne Cs AFS and although more massive, it is expected to be longer lived and more immune to environmental changes [7].

The temperature variation in orbit can lead to pronounced frequency changes in the Rb AFS [8] and to a lesser extent in the Cs AFS [9]. The Rb AFS are sensitive enough that +0.1 C active temperature control was implemented [8]. Temperature variations experienced by the s/c and on-board clocks are strongly correlated to the NAVSTAR orbit orientation relative to the earth-sun line. For example, twice a year, for about a 25 day interval, NAVSTAR 16 goes into the earth's shadow during a portion of each 12 hour orbit. This causes a 1-3 C drop in the average temperature of the s/c and frequency pulling of the CAFS ranging from $2\text{-}7\times10^{-13}$ [9].

H-masers

Although several H-maser frequency standards have been developed for spaceborne applications [10-14], only the NASA/SAO Gravity Probe A suborbital flight (June, 1976) has carried an ultra-stable frequency standard into space [2,15]. In a 2 hour flight a 45 kg H-maser was lifted to an altitude of 10,000 km above the earth's surface where the gravitational redshift speeds the clock rate by 4×10^{-10} relative to an earth based clock. The measured H-maser stability in flight was $\sigma_y(\tau=1000 \text{ secs})=6\times10^{-15}$ and verified the gravitational redshift as predicted by Einstein's General Relativity to about 1 part in 10^4.

Table II summarizes some physical characteristics of two, more recently developed H-masers for space based operations [11-13]. These H-masers are higher performance but somewhat more massive than the 1976 GP-A maser. The mass of the maser is made large by the large size of the high Q TE_{011} cylindrical cavity together with the inherent magnetic sensitivity of the hydrogen atom. Typically 4 to 5 layers of magnetic shielding are required to prevent ambient field changes from pulling the atomic frequency and degrading stability. The shields must be large enough to enclose the approximately 30 cm(12") diameter cavity and consequently contribute 38 kg to the total $\approx$70 kg mass of the maser [12]. A dielectrically loaded cavity of reduced size for space based H-maser applications with somewhat reduced performance is described in ref [14].

Cs Clock parameters	GPS	GLONASS
Mass	13 kg (Block II) 8 kg (Block IIR) (29-17 lbs)	40 kg (GEM) 52 kg (MALAKHIT) (88-114 lbs)
Power (Watts)	26 W (II) 23 W (IIR)	80 W (GEM) 90 W (MALAKHIT)
Package Size (mm) (inch)	150x150x430 6x6x17	414x421x655 16x16x26
Stability, $\sigma_y(\tau)$ 1 day 10 days Frequency Drift	1.5×10^{-13} $4\text{-}5 \times 10^{-14}$ $\pm$few$\times 10^{-15}$/day	$1\text{-}5 \times 10^{-13}$ $7\text{-}25 \times 10^{-14}$
Temperature Sensitivity	$1\text{-}2 \times 10^{-13}$/C no active control	$2\text{-}5 \times 10^{-13}$/C

Table I: A summary of present day space based Cesium atomic frequency standards in use in the GPS and GLONASS programs.

H-maser parameters	NASA/SAO	ESA
Mass	67 kg	70 kg
Power	55 Watts	70 Watts
Size	17"OD$\times$34"h (44cm$\times$86cm)	14"OD$\times$27"h (35cm$\times$70cm)
Stability, $\sigma_y(\tau)$ 10^3 to 10^4 sec 1 day	$\leq 10^{-15}$ few$\times 10^{-15}$	$\leq 10^{-15}$ few$\times 10^{-15}$
Temperature Sensitivity	requires 10^{-4} C temperature control	requires 10^{-4} C temperature control
Magnetic Shielding Ref [11-13]	5 layers & active field compensation 2×10^6 axial shielding	4-5 layers

Table II: A summary of two recently developed hydrogen maser frequency standards for use in space based applications.

Review of the Linear Ion Trap Extended (LITE)

The proposed space-borne frequency standard discussed in this paper is based upon the Hg^+ extended linear ion trap [17] currently under development at the JPL Frequency Standards Lab. This new linear ion trap architecture separates the resonance region (where the multiplied output of the local oscillator is compared to the stable atomic frequency) from the state-selection/state-interrogation region where the ions are optically pumped into the lower atomic hyperfine state. The charged ions can easily be moved from one region to another along the axis or node line of a single extended linear ion trap. One end of the extended linear trap serves as the state selection region with an optical system, etc. while the other end serves as the resonance region with a 40.5 GHz microwave source, magnetic shields, etc. Only the microwave resonance region need be magnetically shielded and since there are no optics in the resonance region (unlike the previous design [18]) the shields can be made quite small.

The LITE frequency standard now being developed at JPL is shown in Fig. 2. This first laboratory version is 18" in length with a 5 1/4" od triple layer set magnetic shield around the resonance region. This particular version can be reduced in size by about one-half by use of cylindrical electrodes as described in Ref [19]. In the resulting smaller trap, the cylindrical electrodes would also be the vacuum wall additionally removing the need for electrical feedthroughs. In this manner a linear ion trap of diameter $\leq$1" with several eV well depth for Hg^+ ions could be constructed. This is much smaller than the diameter of a Cesium beam tube.

Table III shows a breakdown of the contributors to the mass of an ion trap of the architecture discussed above. The trap is assumed to be about 16" long with an diameter of 1". The state selection\ion loading region is about 4" with the resonance region making up 12" of the length. The triple layer magnetic shield is assumed 14" long with 1/2" spacing between layers. These design estimates are based on and extrapolated from Hg^+ trap systems which have demonstrated performance well below 10^{-15} [20].

The support electronics are to a large extent similar to those of a generic Cesium frequency standard. For example, since they are both passive frequency standards, a frequency multiplier chain from the local oscillator to the atomic resonance frequency is necessary, to 40.5 GHz for Hg^+ and to 9.2 GHz for Cs. Table IV shows the support electronics that are common to both units and some additional electronics required by the Hg^+ standard. A very good crystal VCXO [21] would enable the Hg^+ standard to reach few parts in 10^{16} stability at $\tau=10^5$ seconds, i.e., $2\times10^{-13}/\sqrt{\tau}$. This is more than is required for Cesium standard operation but such LOs exist and have been space qualified [21]. The state of the art for space qualified Cs standards are the GPS Block IIR [6], having undergone a few generations of refinement in the GPS clock development program. The super VCXO is about 1760 gms [21] while the GPS Block IIR Cesium VCXO is about 315 grams as shown in table IV.

Mass Estimate for the Hg^+ LITE Standard

Taking the Block IIR Cesium as current state of the art for compact space qualified Cs standards, we estimate the mass of a space qualified Hg^+ clock. The Cesium standard of IIR design has total mass 7.7 kg (17 lbs) of which the Cesium tube contributes 4.1 kg (9 lbs) [6]. Our Hg^+ tube is estimated in Table III to be somewhat heavier at 5.4 kg. Table IV shows that the electronics package for an Hg^+ clock with ultra-stable performance is 1760-315+500 = 1945 gms more in mass (primarily because of the better LO). We thus arrive at a mass estimate for an Hg^+ standard of 1.945 + 1.3 $\approx$ 3.2 kg more than the Block IIR Cesium mass of 7.7 kg, that is, a space qualified Hg^+ standard of mass 10.9 kg. This estimate is uncertain by about 1 kg since efficient packaging can be difficult to estimate before full miniaturization is implemented. There is little doubt, however that a high performance Hg^+ clock could be built that is $\leq$20% of the mass of the proposed space qualified H-masers.

Hg^+ LITE Consumables

The Hg^+ standard described here needs a supply of Helium (to be used as a buffer gas) and, of course, Hg for the generation of ions. In ground based laboratory ion trap standards, helium operating pressure is about 10^{-5} Torr and is pumped away into a vacuum pump at a speed of about 1 liter/second. This throughput of 10^{-5} Torr liters/second would deplete a 1 liter helium bottle filled to 5 atmospheres in just over 12 years.

Similarly, the mercury vapor in an operating Hg^+ standard is at a pressure of 10^{-9} Torr or less and is pumped at even less speed than the helium. The mercury is thus consumed at a rate of less than 1 milligram per 3 years, again showing no problem in depleting the supply of mercury.

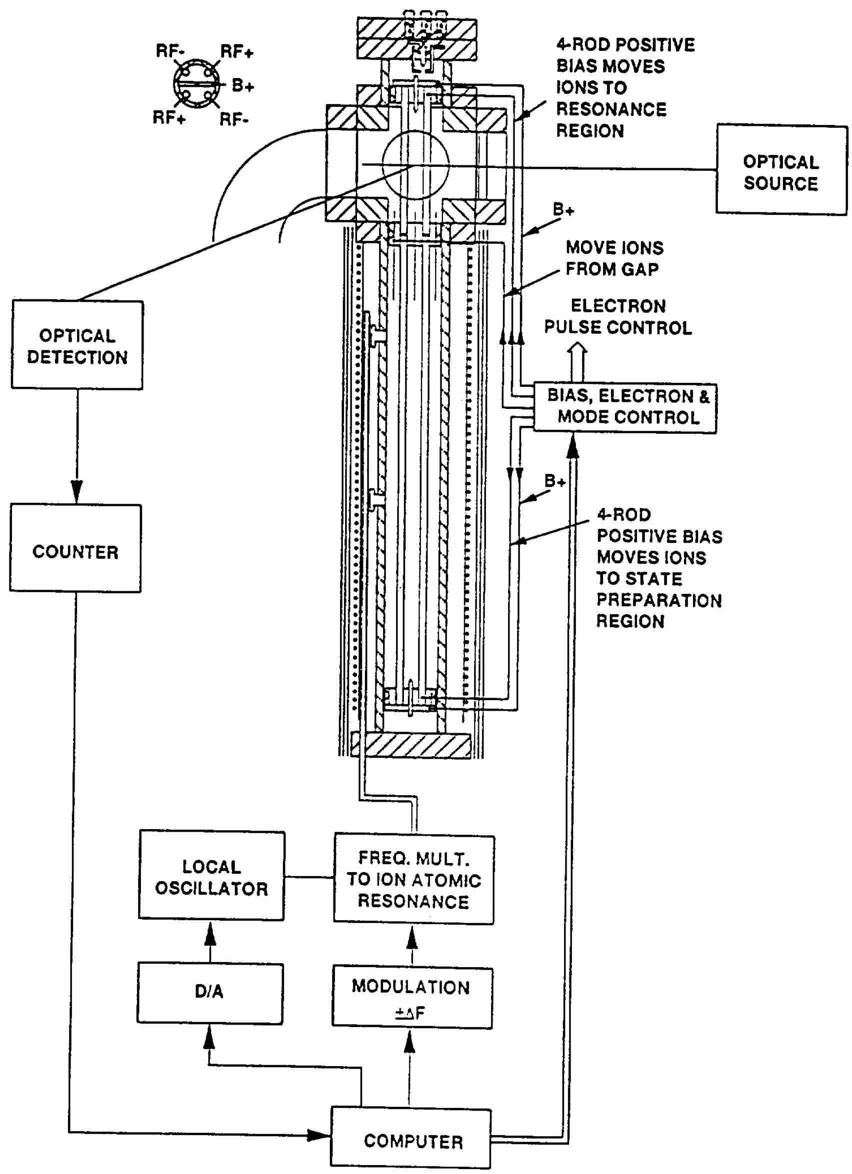

Figure 1: Schematic view of the linear ion trap extended architecture. The state preparation region is at the upper end of a ≈40 cm long linear trap. A dc break separates the resonance region (lower part of the long trap) from the upper part. By applying dc biases, ions are moved from the state selection region into the microwave resonance region and then back. Only the microwave resonance region need be magnetically shielded, etc. The resulting physics package is comparable in size to a cesium beam tube.

Vacuum can/Trap electrodes	790 gm
Triple layer Magnetic Shield	227 + 409 + 590 = 1226 gm
HgO Oven	150 gm
Fused Silica Windows & Mount	150 gm
Lamp & Mount	150 gm
Collection Mirror, Lens & Mount	400 + 35 + 500 gm
C-field Coils	250 gm
Electron gun & Mount	10 gm
Getter pump & Ion pump	1000 gm
Helium leak & Storage Bottle	750 gm
Total	5.4 kg

Table III: An itemized list of the contributors to the mass of the Hg^+ LITE atomic frequency standard. This list summarizes components in the physics package of the Hg^+ standard and is analogous to the Cesium beam tube of the Cesium frequency standard.

Electronics	Hg^+ LITE	Cesium
LO to Atom Frequency Multiplier	to 40.5 GHz	to 9.2 GHz
Servo LO to Atom	Microprocessor, Frequency modulation, etc.	modulate, tune VCXO etc.
Bias/power supplies	HgO oven, C-field, ion pump, e-gun, PMT, ion gauge	Cs oven, C-field, ion pump, e-mult, hot wire, ion accel
VCXO	Super VCXO, $\sigma_y=10^{-13}$ 1760 gms	VCXO 315 gm
Additional supplies	Helium leak heater, Lamp driver, Trap rf drive. (Estimate 500 gm)	Not Applicable

Table IV: A comparison of the support electronics for the Hg^+ LITE standard and the GPS Cesium standard. Much of the elctronics is common to both clocks. The Hg^+ clock needs a super VCXO to reach stabilies of a few parts in 10^{16} at 10^5 seconds. Some additional heaters and rf supplies are needed for the Hg^+ standard.

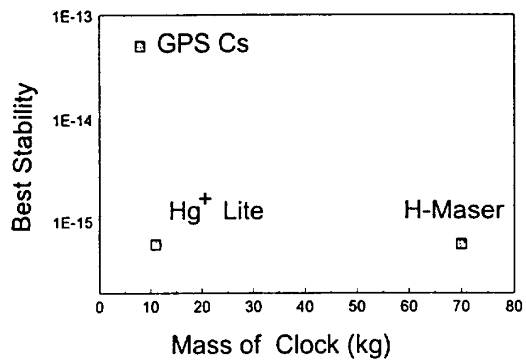

Figure 2. A summary of clock frequency stability vs. clock mass for three space based frequency standards discussed in this paper. The proposed Hg^+ LITE can supply stability of a maser in a total package with mass comparable to the current day GPS Cs standards.

Summary and Conclusions

The ultra-stable Hg^+ standard described here can deliver far more stability per kilogram than any of the present day space based standards. This is graphically illustrated in Figure 2 where H-masers, GPS Cesiums and the proposed Hg^+ standard are plotted on a stability vs. mass diagram. The Hg^+ offers the best of both of the other space based standards, that is, the stability of an H-maser for the mass of a Cesium clock.

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